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# The Spatial Coherence of Electron Wavefunctions and the Transition from Miniband to Stark-Ladder Electric Field Regimes in InGaAs/InAlAs-on-InP Superlattices

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## The Spatial Coherence of Electron Wavefunctions and the Transition from Miniband to Stark-Ladder Electric Field Regimes in InGaAs/InAlAs-on-InP Superlattices

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## Abstract

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Five  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As-on-InP}$  superlattices of various well-to-barrier ratios and miniband widths have been studied by low-temperature photoluminescence, photocurrent, and differential photocurrent spectroscopies. These techniques provide a means of measuring the spatial coherence length of electron wavefunctions in the superlattices. We find that the onset of Wannier-Stark localization occurs when the well-to-well potential drop within the superlattice is between 1.1 and 1.43 times the low-temperature photoluminescence linewidth for all samples studied. Furthermore, the photoluminescence linewidth is accurately describable in terms of a simple model for alloy broadening. These findings confirm an intuitive picture for the transition between the miniband and Wannier-Stark electric field regimes in  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As-on-InP}$  superlattices.

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## 1. Introduction

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The optical and electronic properties of superlattices are of interest to the Army because of the profound effects of superlattices on the operational performance of numerous state-of-the-art optoelectronic and photonic devices. For example, bound-to-miniband quantum-well infrared photodetectors (QWIPs) [1], infrared hot-electron transistors [2], and Wannier-Stark modulators [3] are all devices that both explicitly exploit various advantageous properties of superlattices and are being actively pursued as components in next-generation Army optoelectronic and photonic systems.

This technical report focuses on two aspects of superlattices relevant to their effect on device performance: the superlattice spatial coherence length and the transition from the miniband to the Wannier-Stark ladder electric field regimes. The spatial coherence length is simply the physical extent of the electron wavefunction along the growth direction of the superlattice. Figure 1(a) shows a simplified diagram of a superlattice miniband. When the applied electric field is zero and the barriers between quantum wells are sufficiently thin, the electrons are in principle delocalized throughout the entire superlattice, and the band structure (at  $k_{\parallel} = 0$ ) takes the form of the superlattice miniband shown. At small values of applied electric field, the electrons become localized, but the wavefunction can extend over many superlattice periods. A simple semiclassical picture predicts that the electron becomes localized within a region  $\Delta/eF$ , where  $\Delta$  is the superlattice miniband width,  $e$  is the magnitude of the electron charge, and  $F$  is the electric field. This is the Wannier-Stark regime, shown schematically in figure 1(b). At high electric fields, the wavefunctions become completely localized into one quantum well. This regime is shown schematically as figure 1(c).

Recently, we used photoluminescence (PL), photocurrent (PC), and differential photocurrent spectroscopies at low temperature to study the spatial coherence of electrons in a 30-Å  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ /20-Å  $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  superlattice [4] grown lattice-matched to InP. We learned two important things from this study. First, we measured the PL linewidth at 2 K to be 4.3 meV and found that this linewidth was consistent with the minimum linewidth calculated for an exciton in a semiconductor-alloy superlattice, assuming that the alloy cations are randomly distributed on the group III lattice sites. Second, the longest spatial coherence length measured was 1450 Å at 2 K. This coherence length corresponds to a well-to-well potential drop of 4.9 meV, almost exactly the alloy-broadened linewidth measured in PL.



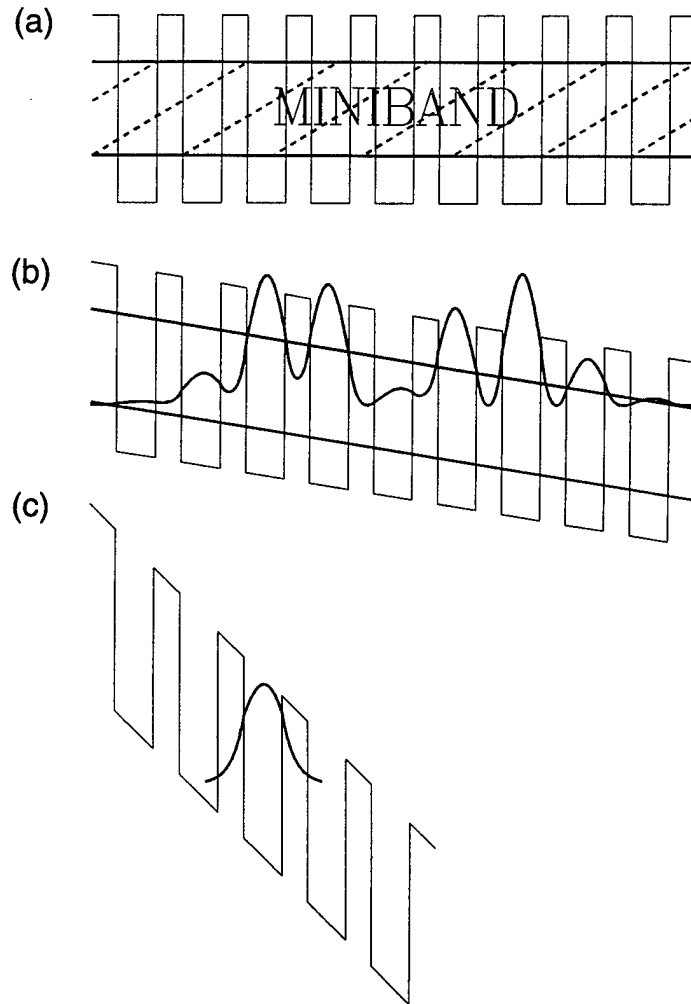


Figure 1. Three electric field regimes of a semiconductor superlattice: (a) miniband regime, (b) Wannier-Stark regime, and (c) high-field regime. In (b) and (c), the electron envelope wavefunctions (squared) are shown; the wavefunction in (b) extends over many superlattice periods and diminishes toward zero, in rough agreement with the classically predicted turning points at the edges of the miniband.

The results of this study suggested a simple intuitive model for the spatial coherence of the electron and the transition from the miniband to the Wannier-Stark ladder electric field regimes. This model is explained briefly as follows. In a real superlattice, the random fluctuations of the alloy potential and the layer thickness fluctuations that underlie the measured PL linewidth create a random potential contribution to the periodic potential of the superlattice. This random potential localizes electronic states that at zero electric field would extend throughout the superlattice. Thus for a real superlattice, the electric field effects associated with the Wannier-Stark electric field regime would be observed only when the Stark-localization length  $\Delta/eF$  is smaller than the coherence length of the electronic states localized by the random potential. The electric field causing the transition between miniband and Wannier-Stark electric field regimes is then defined operationally as the smallest electric field for which the Stark-localization length is smaller than the coherence length of the electronic states localized by the random potential.

The physical model for Stark localization explained above, although intuitively appealing, is based on measurements of only one sample. The results presented below test this model for a wider range of well-to-barrier ratios and several miniband widths. We find that every sample studied shows a transition from the miniband regime to the Wannier-Stark regime in correspondence with the model described above.

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## 2. Sample Description and Experimental Technique

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Figure 2 is a contour plot of miniband width versus superlattice barrier-to-period ratio for  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  superlattices. Each contour is drawn for a given period  $P$ . Figure 2 was generated with a simple Kronig-Penney model (including band-nonparabolicity effects [5]) for the miniband width. The strategy adopted was to study a series of samples of various miniband widths (samples *a*, *e*, and *c* in fig. 2) and also to study two pairs of samples (pairs *a-b* and *c-d* in fig. 2) in which both samples of a given pair had nearly identical miniband widths but widely disparate barrier-to-period ratios.

The samples were grown by molecular-beam epitaxy (MBE) on *n*-doped InP substrates and consisted of 0.25  $\mu\text{m}$  of *n*-doped (In,Al)As buffer layer followed by 0.1  $\mu\text{m}$  of undoped (In,Al)As, 0.8  $\mu\text{m}$  of undoped superlattice, another 0.1  $\mu\text{m}$  of undoped (In,Al)As, 0.2  $\mu\text{m}$  of *p*-doped (In,Al)As, and a 200-Å *p*-doped (In,Ga)As capping layer. All layers were grown nominally lattice matched to the InP. High-resolution x-ray diffraction spectra ((004) reflection) on sample *c* showed a high degree of structural perfection. Near

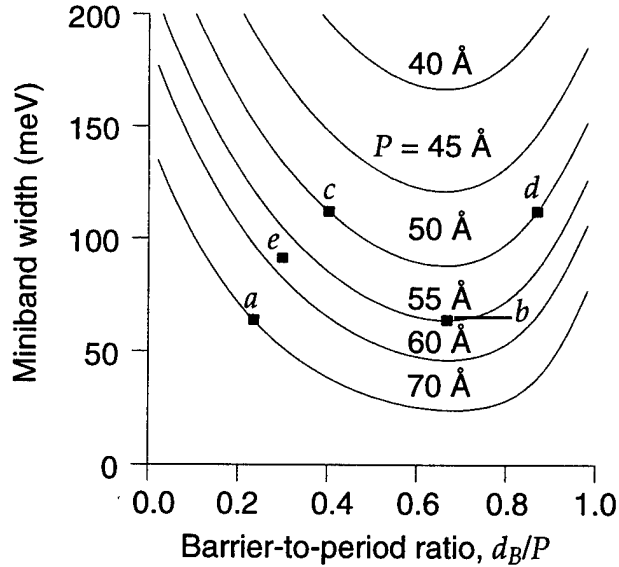


Figure 2. Contour plot of miniband width  $\Delta$  versus superlattice barrier-to-period ratio  $d_B/P$  for  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ -on-InP superlattices. Each contour is drawn for a given period  $P$ . Black squares indicate samples considered in this study.

the (004) InP substrate reflection, the x-ray peaks of the substrate, thick (In,Al)As layers, and superlattice overlap and cannot be individually resolved; we conclude that the average mismatches of these layers must be less than  $2 \times 10^{-4}$ . The first-order satellites in the x-ray spectrum have a full width at half maximum (FWHM) of 23 arc seconds, which is exactly the width that we calculated for these peaks for our diffractometer using dynamical diffraction theory and assuming a perfect structure. From the x-ray data, we conclude that the rms well-width fluctuations for sample *e* are less than 0.02 monolayers (0.06 Å). The other samples were grown under MBE growth conditions that were nearly identical to those for sample *c*, and we therefore expect similar structural quality for these samples.

The PL measurements were conducted with the sample immersed in liquid He pumped below the  $\lambda$  point. The He bath temperature was nominally 2 K. The samples were excited with Ar<sup>+</sup> laser radiation at 514.5 nm and an excitation intensity in the range of 0.1 to 1.0 W/cm<sup>2</sup>. The PL signal was optically chopped, dispersed through a 2/3-m monochromator and detected with an InAs photovoltaic detector. The detected signal was processed by conventional lock-in techniques. For PC measurements, the samples were processed into 500- $\mu$ m-diameter mesa diodes with ring contacts. Chopped light dispersed through a 3/4-m monochromator was focused onto one of the diodes, and the resulting PC signal was measured with a lock-in amplifier. For differential PC measurements, the monochromator wavelength was held fixed while a small ac voltage was placed across the sample in addition to the dc bias, which was varied. The fundamental and second-harmonic ac components of the PC were measured with a lock-in amplifier. These components are proportional, respectively, to the first and second derivatives of the PC with respect to the bias voltage.

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### 3. Results

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Figure 3(a) shows the PL spectrum at 2 K for each of the five samples studied. The interband threshold energy  $E_0$  and the PL FWHM  $\Delta E_{PL}$  are determined from these spectra and recorded in columns 4 and 5, respectively, of table 1, along with other pertinent information. In figure 3(b), the measured PL FWHM is plotted versus the theoretically predicted linewidth calculated according to the alloy broadening model described elsewhere [6]. We find satisfactory agreement between measurement and theory over a wide range of PL linewidths, indicating that alloy fluctuations are the dominant mechanism for PL linewidth broadening in these superlattices.

Figure 4(a) is an example PC spectrum for sample *c*. The spectrum was recorded at a constant energy excitation of 1.016 eV and a variable applied bias. Because the excitation energy is less than the zero-field interband transition energy of 1.088 eV, there is no PC observed at zero electric field. As shown schematically in figure 4(b), PC maxima occur at applied electric fields when the oblique interband transition energies of the superlattice become coincident with the excitation energy. An interband transition between wells separated by  $n$  superlattice periods is denoted by a Stark-ladder index  $n$ . The Stark-ladder indices  $n$  corresponding to PC maxima are labeled in figures 4(a) and (b). The inset of figure 4(a) (solid line) magnifies the

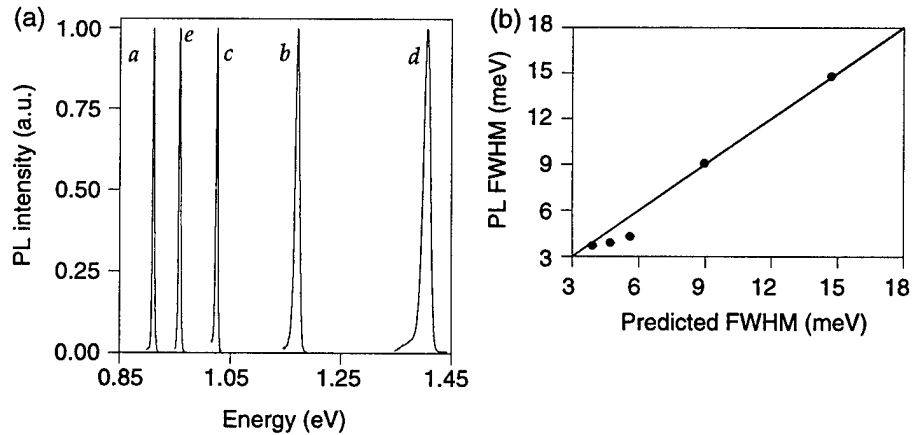


Figure 3. Photoluminescence data at 2 K for samples *a* through *e*: (a) PL spectra: interband threshold energy  $E_0$  is taken as PL peak. (b) Measured PL FWHM from (a) versus theoretically predicted FWHM from alloy-broadening model of reference 6.

Table 1. Structural and optical characteristics of samples considered in this study.

Sample	Barrier-to-well ratio (Å)	Miniband width (meV)	Interband threshold energy $E_0$ (eV)	PL FWHM (meV)	Largest Stark-ladder index at energy $E$ (eV)	Well-to-well drop (meV)	Ratio of col 7/col 5
<i>a</i>	53.6/16.4	61	0.943	3.7	$n = -7$ at 0.901	6.0	1.43
<i>b</i>	36.6/18.4	64	1.21	9.1	$n = -4$ at 1.170	12.5	1.10
<i>c</i>	20/30	120	1.088	4.3	$n = -14$ at 1.024	4.9	1.14
<i>d</i>	43.3/6.7	110	1.480	14.8	$n = -4$ at 1.397	20.8	1.40
<i>e</i>	17/40	80	1.010	3.9	$n = -11$ at 0.955	5.0	1.28

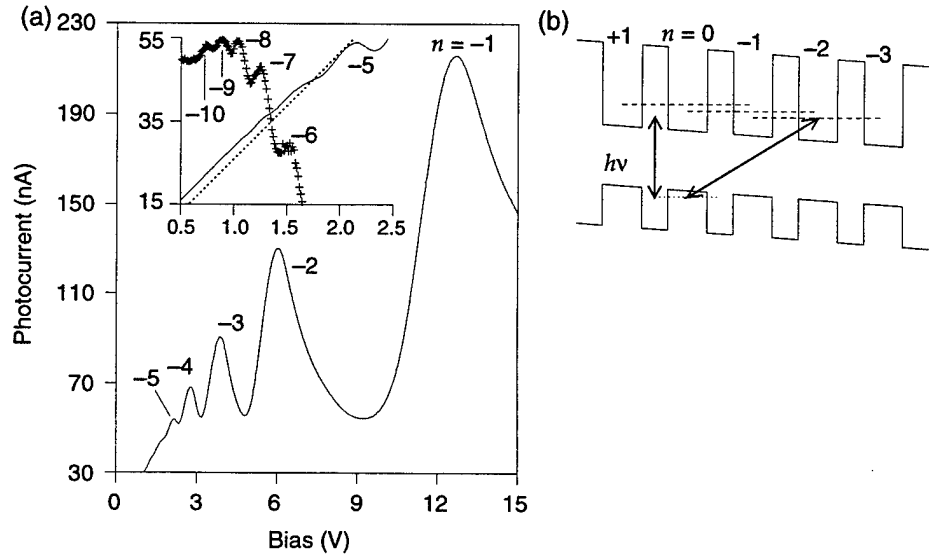


Figure 4. Photoabsorption processes for sample *c*: (a) Photocurrent spectrum of sample *c* taken with below-threshold optical excitation of 1.016 eV and variable applied bias. Wannier-Stark ladder transitions  $n$  are labeled. Inset: magnified view of low-bias region of spectrum (see text), showing oblique Wannier-Stark transitions up to  $n = -10$ . (b) Schematic diagram of oblique optical absorption processes.

low-bias region of the spectrum. The dotted line in the inset is an arbitrarily chosen straight line, and the plotted crosses are the rescaled difference between the spectrum and the dotted line. The crosses reveal oblique optical transitions between wells separated by up to 10 superlattice periods, or 500 Å.

It should be clear, however, that the sensitivity of the PC method to the oblique Wannier-Stark transitions is limited. The inset of figure 4(a) illustrates that one is eventually reduced to looking for small maxima on top of

large dc PC signals. This circumstance suggests that derivative techniques would enhance the sensitivity to oblique transitions with high Stark-ladder indices.

Figure 5 shows PC, first-derivative, and second-derivative spectra at an excitation energy of 1.024 eV for sample *c*. The spectra are plotted as a function of  $F^{-1}$ . The PC spectrum (fig. 5(a)) shows oblique transitions of Stark-ladder index up to  $n = -8$ . The first-derivative spectrum (fig. 5(b)) clearly shows features out to  $n = -14$ . These results are corroborated by the second-derivative spectrum (c), which also contains features out to  $n = -14$ . Note that the maxima of the PC spectra correspond to zeroes (with positive slope) in the first-derivative spectra, and to minima in the second-derivative spectra. Note also that the maxima and minima occur periodically as a function of  $F^{-1}$ , which corroborates the Wannier-Stark origin of these oscillations.

Because of the large heavy-hole mass, heavy-hole superlattice states are confined to a single well even near zero electric field. Thus, the observation of oblique optical transitions corresponds to a measurement of the spatial extent of conduction band Wannier-Stark states. The  $n = -14$  Stark-ladder transition for sample *c* is observed at a field of 10 kV/cm. This field corresponds to a well-to-well potential drop of 4.9 meV. At such small electric fields, the electron wavefunction is approximately symmetric about the central quantum well. For example, the electron envelope wavefunction plotted in figure 1(b) is calculated with the well and barrier thicknesses of sample *c*, and an electric field of 28 kV/cm. Thus, the observation of the  $n = -14$  Stark-ladder transition indicates that the electron wavefunction extends over 29 superlattice periods, or 1450 Å.

PC, first-derivative, and second-derivative spectra were also measured for the other four samples. For each of these samples, we determined the well-to-well potential drop corresponding to the highest Stark-ladder transition observed. These results are recorded in column 7 of table 1.

The last column of numbers in table 1 is the ratio of the well-to-well potential drop at the onset of Stark-localized behavior (column 7) to the measured PL linewidth (column 5). The numbers in this column vary between 1.10 (sample *b*) and 1.43 (sample *a*). For all samples studied, we find that the Wannier-Stark ladder becomes observable when the well-to-well potential drop is between 1.1 and 1.43 times the PL linewidth. This observation validates the intuitive picture proposed for the transition between the miniband and Wannier-Stark electric field regimes.

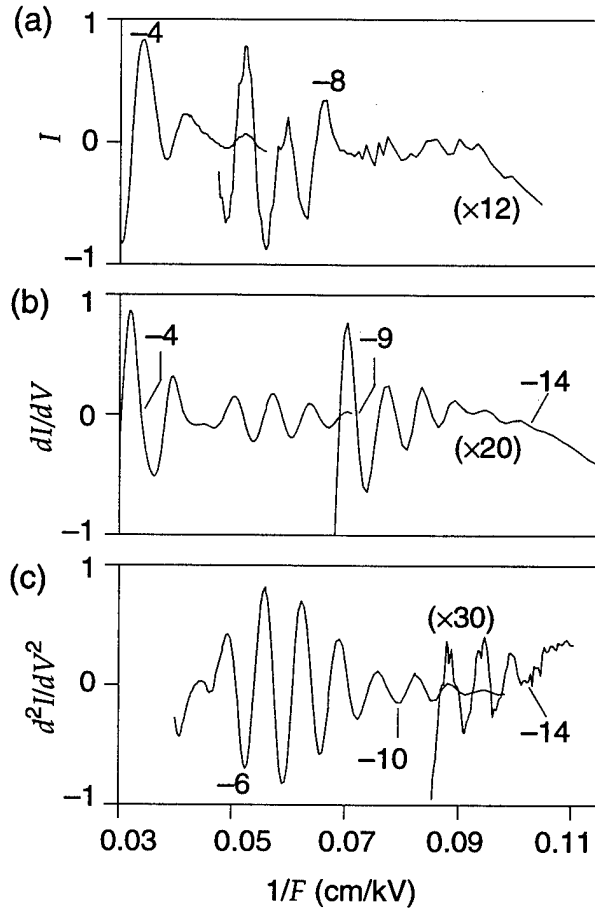


Figure 5. Spectra of superlattice sample *e* at an excitation energy of 1.024 eV: (a) photocurrent, (b) first derivative, and (c) second derivative. Wannier-Stark ladder transitions  $n$  are labeled.



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## 4. Summary and Conclusions

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We have shown that the spatial coherence length of electron wavefunctions can be accurately measured by means of first- and second-derivative PC spectroscopy. We note in particular the results for samples *c* and *e*. The largest Stark-ladder index observed for these superlattices is  $n = -14$  and  $-11$ , respectively. This corresponds to spatial extents of the electron wavefunctions of 29 and 23 superlattice periods, or 1450 and 1310 Å, respectively. These coherence lengths are longer than the longest yet reported in the literature [7–9].

In all samples studied, we find that the superlattice miniband breaks up into the Wannier-Stark ladder when the well-to-well potential drop in the superlattice is between 1.1 and 1.43 times the low-temperature PL linewidth. Furthermore, the PL linewidths of all the samples studied are in reasonable agreement with a simple theoretical treatment [6] of linewidth broadening due to alloy fluctuations of the constituent superlattice materials.

These results confirm the following intuitive picture for the transition between the miniband and Wannier-Stark ladder electric field regimes in  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As-on-InP}$  superlattices. At zero electric field the superlattice electron states are localized. This localization is due to random fluctuations of the alloy potential and layer thickness fluctuations that underlie the observed PL linewidth. Thus, electric field effects associated with the Wannier-Stark regime are observed only when the Stark localization length  $\Delta/eF$  is smaller than the coherence length of the electronic states localized by the random potential.

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